CARBON RESERVOIRS IN PROTOPLANETARY SYSTEMS SURVEYED ACROSS THE GALAXY.

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Introduction: High-resolution near-infrared observations of carbon monoxide (CO) gas toward young stellar objects (YSOs) enable precise evaluation of carbon and oxygen isotopes in these systems, which in turn lead to valuable insights into protoplanetary processes [1-6]. Comparisons made between solar system materials and young stellar gas further the understanding of phenomena that could have affected chemistry in the early solar nebula, including CO self-shielding [3,6], supernova enrichment [4], and the potential interplay between CO ice and gas reservoirs [5,6]. Such astronomical observations also enable the study of potential differences in chemical pathways between isolated cores and low-mass binary systems separated by a few hundred AU [5]. In contrast to low-mass YSOs, massive YSOs (>~ 8 solar-masses, ~ 10^3 to 10^5 solar-luminosities) trace high-UV fields, permitting observations over a significant range of Galactocentric radii (R_{GC}). Further, since precise abundances of gas-phase $^{12}C^{16}O$ (^{12}CO) and $^{13}C^{16}O$ (^{13}CO) isotopologues can be compared to ice-phase $^{12}C/^{13}C$ from CO and CO_2 ice reservoirs along a single line of sight toward massive YSOs, these are particularly valuable targets in evaluating protoplanetary and prebiotic carbon chemistry. Here we present results from a completed phase of our Keck survey of massive YSOs at R_{GC} from ~0.01 kpc (at the Galactic Center) to ~ 9.7 kpc (just beyond the local solar neighborhood).

Observations and Methods: Our latest data set includes 19 massive YSOs, 5 low-mass YSOs, one background star, and 2 Galactic Center (GC) stellar targets; these GC targets -- SgrA* (the nearest star to the supermassive black hole), and GCS 3 at the GC radio arc -- are lines of sight intercepting dense clouds and diffuse ISM near the GC [7], providing insight into chemistry near this unusual star-forming region of the Galaxy. Fundamental (υ=1−0, 4.7 μm) and first-overtone (υ=2−0, 2.3 μm) rovibrational absorption spectra were obtained with the NIRSPEC instrument at high spectral resolution (R~25,000, or 12 km s^{-1}). Analyzed lines were optically thin, with ^{13}CO, $^{12}C^{18}O$ and $^{12}C^{17}O$ derived from the (υ=1−0), and ^{12}CO from the (υ=2−0) bands. Equivalent widths for each line were derived using polynomial + Gaussian fits. A curve of growth and rotational analysis were simultaneously used to derive the Doppler broadening, integrated gas temperatures, and total molecular column densities for each YSO target. Our customized IDL pipeline and codes were used for all data reduction and analyses.

Results: Doppler broadening in the CO lines ranges from 2 to 9 km/s, and gas temperatures range from cold (T ~ 10 to 20 K) to warm (T ~100 to 200 K) regimes, with only cold gas observed toward embedded massive cores. Results thus far show that [^{12}CO]/[^{13}CO] ratios from cold gas surrounding massive YSOs seem to follow a general Galactic metallicity trend, with the lowest value (31±5) found toward GCS 3 (R_{GC} ~ 0.03 kpc). This finding differs from the gas-phase [^{12}CO]/[^{13}CO] heterogeneity found toward solar-type YSOs (R_{GC} ~ 8 kpc) [6]. Further, we find that [^{12}CO]/[^{13}CO] ratios derived from cold gas differ significantly from solid-phase [$^{12}CO_2$]/[$^{13}CO_2$] [8] along the same lines of sight. A particularly notable result is Elias 29, a complex solar-type YSO with dramatically higher [^{12}CO]/[^{13}CO] (228±21) compared to solid [$^{12}CO_2$]/[$^{13}CO_2$] (81±3.7), a difference that could be due to the distinct radiation and velocity fields in this YSO [9]. For both massive and low-mass YSOs, [^{12}CO]/[^{13}CO] ratios from warm gas are consistently higher than those from cold gas, and CO gas reservoirs may be similarly affected by CO ice in these systems. Finally, we find significantly higher [^{12}CO]/[^{13}CO] ratios as compared to those from radio (emission line) observations of the rare isotopologues, $^{12}C^{18}O$ and the doubly-substituted $^{13}C^{18}O$ [11]), which is possibly due to the higher photodissociation rate for $^{12}C^{18}O$ versus $^{13}C^{18}O$ [12].

Conclusions: We have completed a main phase of our YSO observational survey using Keck-NIRSPEC. Results thus far from analyzing [^{12}CO]/[^{13}CO] in protoplanetary gas across the Galaxy are: 1) cold CO gas observed toward massive YSOs follows a Galactic metallicity gradient, in contrast to heterogeneity observed toward low-mass (solar-type) YSOs; 2) CO_2 may follow more complex chemistry than simple inheritance from CO; 3) CO ice may affect CO gas-phase reservoirs in a range of protoplanetary environments; and 4) CO reservoirs may be similarly affected by warm-phase chemistry in both low- and high-mass systems. This study should inform nebular models where YSO properties and Galactic location may have significant effect on protoplanetary and prebiotic carbon chemistry.

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